GRACE 327-750
(GR-GFZ-AOD-0001)

Gravity Recovery and Climate Experiment

AOD1B Product Description Document

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Frank Flechtner
GeoForschungszentrum Potsdam
Department 1: Geodesy and Remote Sensing

Prepared by:

_____
Frank Flechtner, GFZ
GRACE Deputy Science Operations Manager

Contact Information:
    GeoForschungsZentrum Potsdam
    Department 1: Geodesy and Remote Sensing
    C/o DLR Oberpffaenhofen
    D-82234 Wessling
    Germany
    Email: flechtne@gfz-potsdam.de

Reviewed by:

Srinivas Bettadpur, UTCSR, GRACE Science Operations Manager

Victor Zlotnicki, JPL, GRACE Science Team Member

Approved by:

_____
Byron D. Tapley, UTCSR
GRACE Principal Investigator

_____
Christoph Reigber, GFZ
GRACE Co-Principal Investigator

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Document Change

Issue	Date	Pages	Description of Change
Draft	22.09.2003	all	First version
1.0	22.10.2003	all	Included GRACE project comments on draft version

1   Introduction

GRACE data processing requires the removal of short term mass variations in the atmosphere and in the oceans because these mass changes cause time variant gravity field forces acting on the orbiting satellites. These time varying forces have to be taken into account during data processing, if they are not eliminated by repeated observations within short periods. Due to the mission profile of GRACE (and also the CHAMP and GOCE missions) this generally is not the case. Therefore, the effect has to be removed prior to or during the gravity field determination process. For computing these time variations in the gravity field mainly external data sources have to be used.

The following sources for gravity field variations are known:
- High frequency variation sources: Tides (improved tide models are necessary for all missions); Atmosphere; Oceans; Continental water (snow, ice, hydrology).
- Seasonal variation sources: Atmosphere; Oceans; Continental water; Ice mass

For GRACE data processing only the short term variations are of importance, because with the monthly GRACE gravity field solutions it is planned to provide data for determination of the seasonal variations.
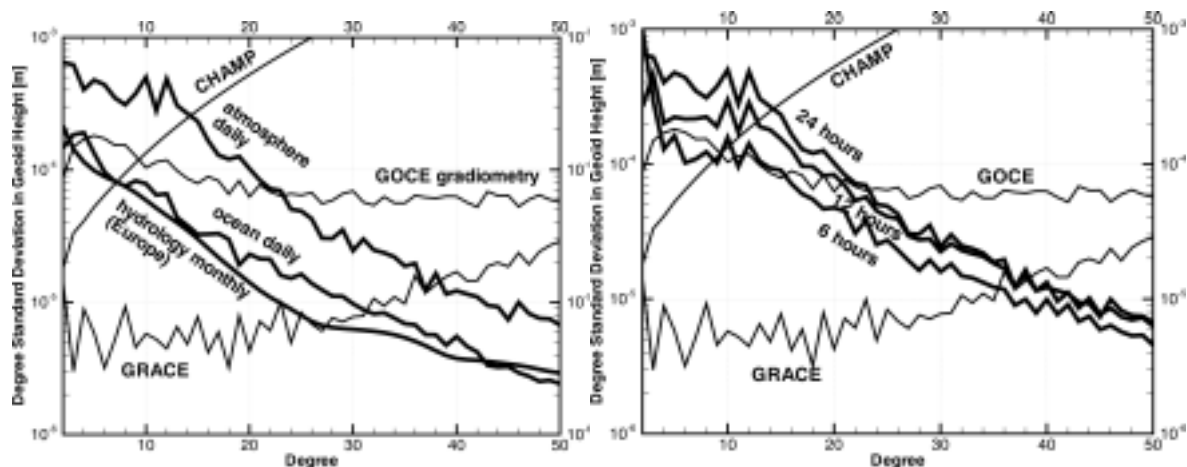

Figure 1-1: Gravity variation signals from different sources in different time scales compared to mission sensitivities (from left to right): a) Comparison of daily atmosphere, daily oceanic and monthly hydrological signals. b) Comparison of 6, 12 and 24 hourly ECMWF signals.

Figure 1-1 shows the effect of some of these mass variations in the gravity field in terms of degree standard deviations in comparison to the expected performance of the three gravity field missions. It clearly becomes visible, that the high frequency mass variations in the atmosphere have impact to all three gravity missions and therefore have to be reduced very carefully. It also becomes visible, that high frequency mass variations in the oceans are much smaller than in the atmosphere, but still have impact on CHAMP and GRACE observations. Because the GOCE gradiometer measures second derivatives of the gravity potential, the sensitivity of the gradiometer to long wavelength mass variations is much smaller. But, as GOCE also carries a GPS receiver, a similar error spectrum as for CHAMP can be expected for the long wavelengths. This means, when combining high-low SST and gradiometer observations of GOCE also oceanic mass variations have impact on the GOCE solution. A similar signal is visible from the monthly hydrology signal over Europe (precipitation minus evaporation). GRACE will detect this long wavelength signal by computing monthly gravity models and comparing them in their sequence of time. It becomes clear, that these monthly variations in the continental water have impact on GOCE, because there are no observations over a full year. Similar signals are caused by seasonal variations in the atmosphere and the oceans. Consequently the monthly GRACE gravity field solutions have to be used for removing this so-called seasonal bias from the GOCE observations.

The document describes in chapter 2 the used meteorological input data and the barotropic ocean model provided by Victor Zlotnicky (JPL) and implemented at GFZ Potsdam. Because the AOD1B (atmosphere and ocean de-aliasing level-1b) product has to be provided to the GRACE Science Data System within 11 days for level-2 gravity field processing the input meteorological data have to be acquired on a routine basis within a short time interval. Therefore GFZ has signed a contract with the German Weather Service (DWD) to regularly acquire the necessary ECMWF fields. ECMWF surface pressure data have been compared with sample NCEP reanalysis and DWD global model surface pressure fields to investigate the influence of data sets of different weather services on the calculated geoid variation.

In chapter 3 the processing strategy to derive atmospheric and oceanic geoid height changes is described. For the atmosphere two mathematical approaches have been investigated. A simplified formula immediately transforms the surface pressure to spherical harmonic gravity coefficients by spherical harmonic analysis of a single layer on the Earth surface (up to degree and order 100). A more complicated, but physically correct approach, performs the vertical integration of the atmospheric density and computes then the gravity coefficients by spherical harmonic analysis. The mean atmosphere and ocean fields needed to derive residual mass variations are described as well as the combination of the atmospheric and oceanic contributions. Because presently no global hydrological models with sufficient accuracy and resolution are available, corresponding short-term variations due to continental water redistribution are not considered here.

Chapter 4 describes some statistical output derived during the generation of the AOD1B product. In chapter 5 the formats of the AOD1B and OCN1B (output from the barotropic model run) products are explained. The document is supplemented by a list of references and abbreviations.

Acknowledgements

2 Input Data and Models

For the calculation of the GRACE Level-1B de-aliasing AOD1B product different atmospheric fields and a ocean model are required. In the following chapters the input data and the ocean model are described.

2.1 Atmospheric Data

For the de-aliasing analysis atmospheric data from 3 different Numerical Weather Services are available: Deutscher Wetter Dienst (DWD), National Center for Environmental Predictions (NCEP) and European Center for Medium-range Weather Forecast (ECMWF). The required fields for this analysis shall be available with a spatial resolution of 0.5° and a temporal resolution of 6 hours. While the ECMWF fields fulfill this requirements, the DWD and NCEP fields are only available at GFZ for dedicated time periods (days to weeks) and have a lower spatial resolution (0.75° resp. 2.5°).

GFZ regularly extracts operational analysis data at the ECMWF Integrated Forecast System (IFS) at synoptic times 0:00, 6:00, 12:00 and 18:00. Details on the used models can be found at http://www.ecmwf.int/research/ifsdocs/index.html. The spatial resolution is defined on a gaussian n160 grid which corresponds to 0.5°. The temperature and the specific humidity is given for 60 layers (surface up to 0.1 hpa). The acquired fields are

- Surface Pressure (PSFC)
- Wind Speed in U and V direction (U10, V10)
- Sea Surface Temperature (SST)
- Dew Point Temperature at 2m level (TDEW2M)
- Temperature at 2m level (TEMP2M)
- Multi-level Temperature (TEMP)
- Multi-level Specific Humidity (SHUM)
- Geopotential Heights at Surface (PHISFC)

and are available at GFZ´s Information System and Data Center (ISDC) for the time span starting on July 1, 2000 until today.

To show the differences in geoid height variations some tests have been performed using surface pressure data from DWD, NCEP and ECMWF which are described below.

2.1.1 Comparison of DWD, NCEP and ECMWF Surface Pressure Fields

The following 3 figures represent the surface pressure for February 23, 2001 as derived from DWD, ECMWF and NCEP.
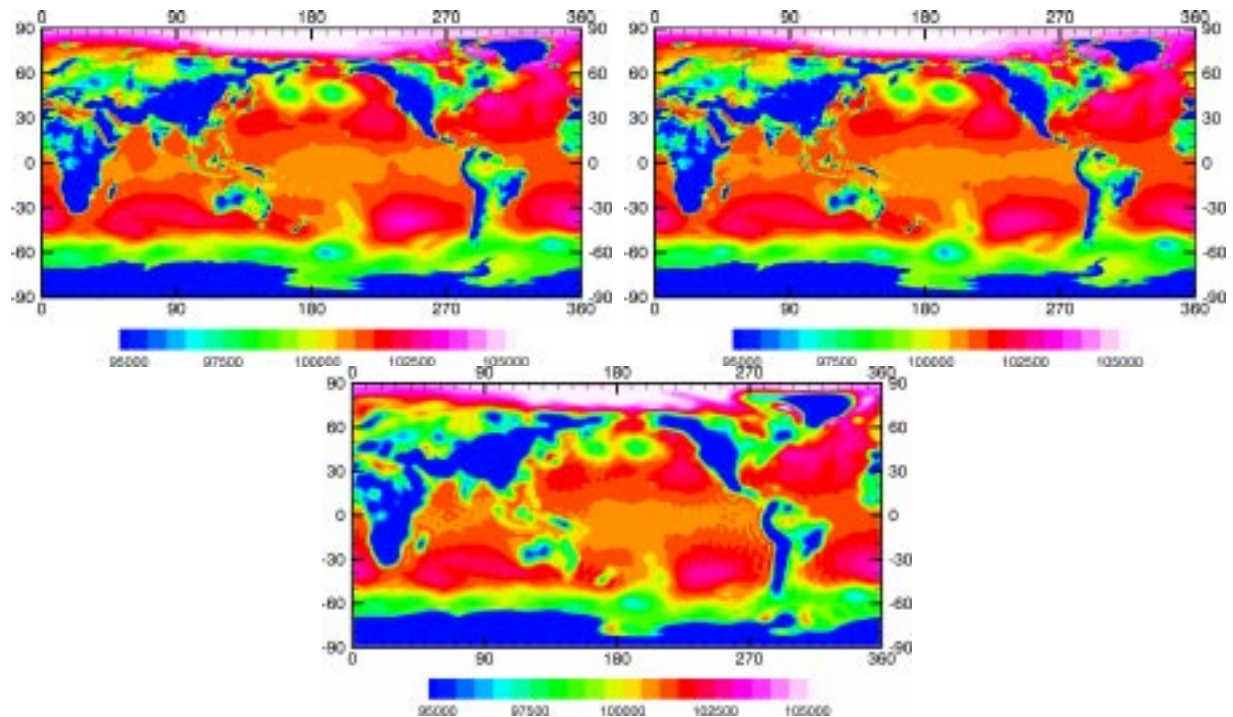
Figure 2-1: Surface pressure from 23. Feb. 2001, 00h: DWD (upper left) global model (resolution 45'), ECMWF (upper right) operational analysis (resolution 30') and NCEP (lower middle) re-analysis (resolution 2.5 degree)

From these surface pressure fields for various time steps gravity field spherical harmonic coefficients are computed (without subtraction of the mean field). In order to identify the signal changes within 6, 12, 18 and 24 hours coefficient differences are plotted in terms of geoid height degree standard deviations. Further on these coefficients are translated into geoid height changes and differences of geoid height changes for the three atmospheric models for the four time steps.

2.1.2 *Spherical harmonic coefficient differences for different time intervals*

The lower signal of the NCEP re-analysis partly is caused by the lower resolution of the model with respect to both other models. But the main reason still is the smaller signal in the NCEP model.
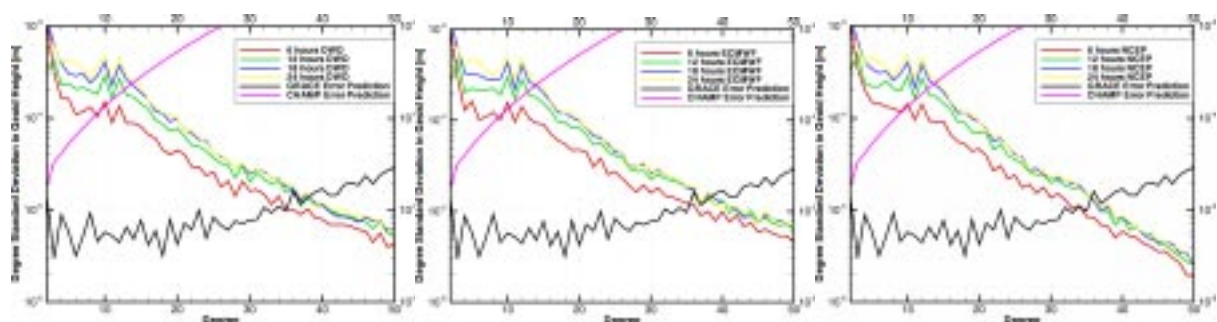
Figure 2-2 Gravity variations in terms of geoid height degree standard deviations with mission error predictions

2.1.3 Geoid height variation based on ECMWF surface pressure for different time intervals

The following figure shows the geoid height variation based on ECMWF operational analysis surface pressure data of February 23, 2001 for 6, 12, 18 and 24 hours respectively. The variation has been calculated by subtraction of a 2001 surface pressure mean field from the actual 6-hourly fields.
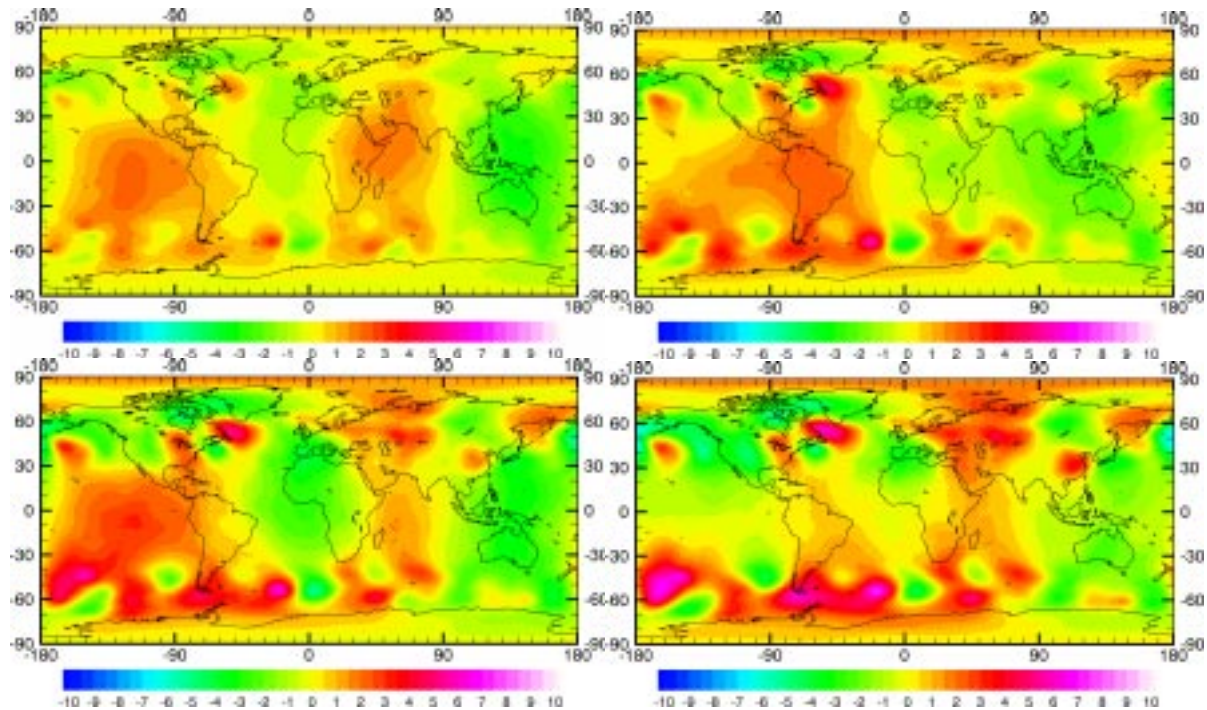
Figure 2-1: Geoid height variations for ECMWF operational analysis on February 23, 2001 (upper left: 6 hours, upper right 12 hours, lower left 18 hours, lower right 24 hours time difference, all in [mm])

2.1.4 Differences of geoid height variations for different time intervals and different atmospheric analysis centers

The following figures show the differences between geoid height variations for February 23, 2001 for 6, 12, 18 and 24 hours derived from ECMWF and DWD and ECMWF and DWD surface pressure data, respectively.
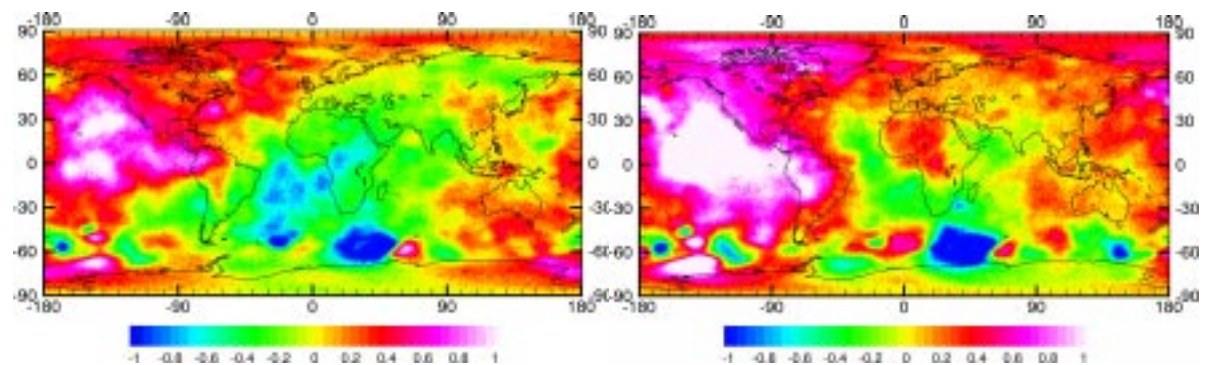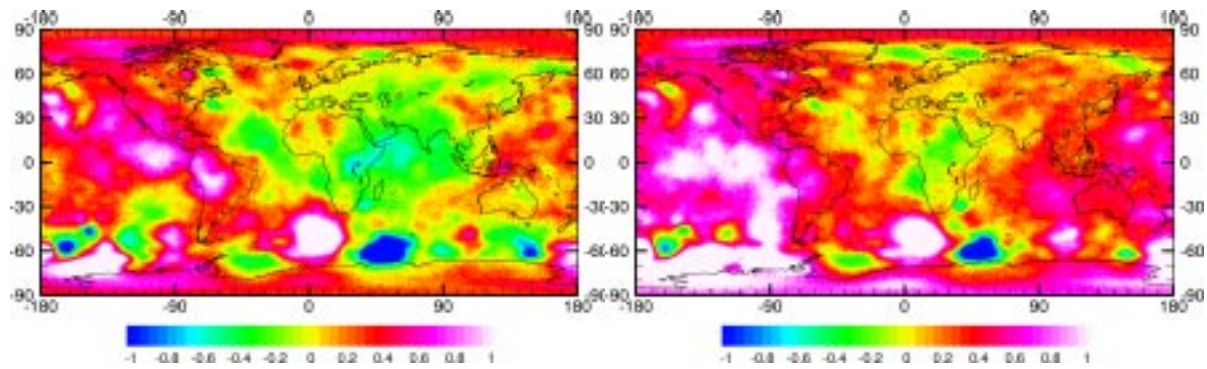
Figure 2-4: Differences of geoid height variations between DWD global model and ECMWF operational analysis on 23.Feb. 2001 (upper left: 6 hours, upper right 12 hours, lower left 18 hours, lower right 24 hours time difference, all in [mm])
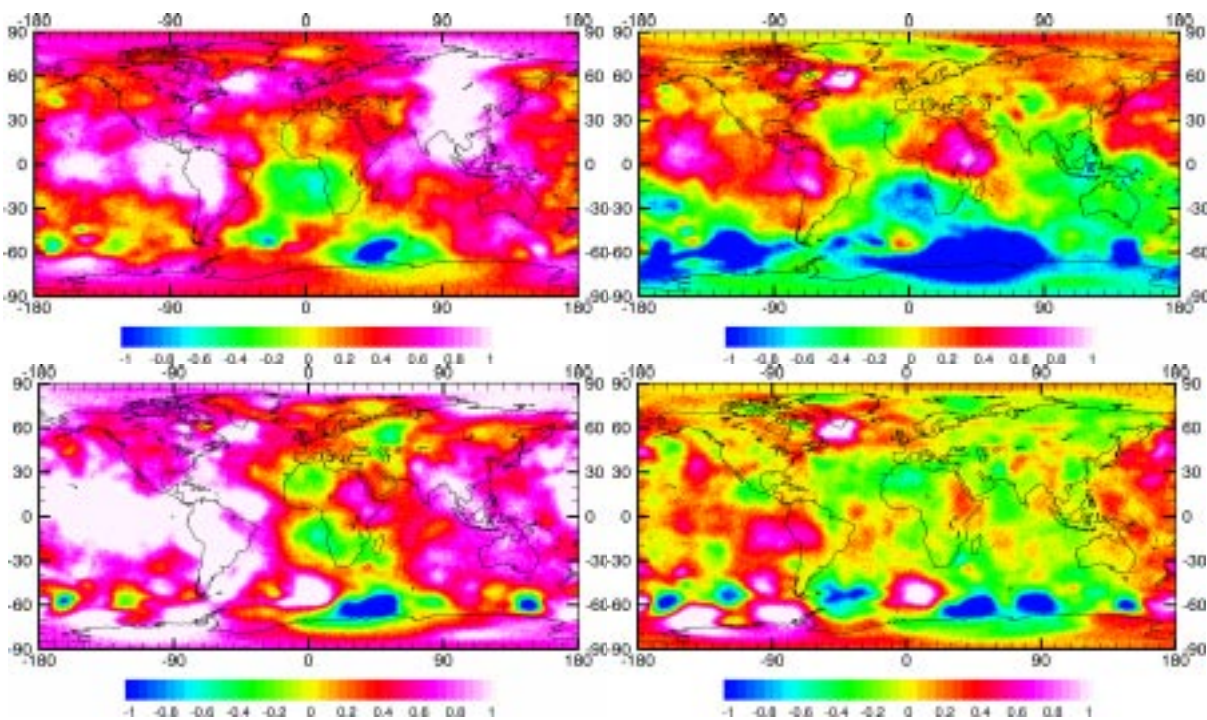
Figure 2-5: Differences of geoid height variations between NCEP re-analysis and ECMWF operational analysis on 23.Feb. 2001 (upper left: 6 hours, upper right 12 hours, lower left 18 hours, lower right 24 hours time difference, all in [mm])

2.2   Ocean Model

For the operational calculation of the atmosphere/ocean de-aliasing product a barotropic or baroclinic ocean model is required. A barotropic ocean model was provided to GFZ by JPL in July 2002.

Some details which describe the model in more general terms are given in the following (courtesy by V. Zlotnicki, October 22, 2003). Further details can be found in (Ali and Zlotnicki, 2003) and (Ponte and Ali, 2002) which exactly used this ocean model implementation. Chapter 6 gives a list of related literature.

Chapter 3.1 describes the barotropic ocean model implementation and processing strategy at GFZ.

ALGORITHM TITLE: Barotropic Ocean Model for GRACE Dealising.

ALGORITHM NUMBER: (not assigned)

ALGORITHM VERSION: PPHA 1.1

HERITAGE: NONE.

PREPARED BY: Victor Zlotnicki <vz@pacific.jpl.nasa.gov>, 1-818-354-5519

LAST UPDATED: 2003-10-01

FUNCTION: This algorithm computes the component of oceanic mass redistribution due to wind and pressure, with periods between 1 day and approx. 60 days. The purpose is to remove the gravity effect of this mass signal from those measured by GRACE before combining data for several weeks to make a gravity field estimate. This minimizes aliasing of fast signals from the ocean (too fast to be properly sampled by GRACE) into the n-weekly gravity estimates. Note: ocean mass redistribution over similarly short timescales, but due to tidal forcing, are computed in another algorithm. It is intended that the output of this model over the oceans be combined with atmospheric mass distribution on land before converting to spherical harmonic mass distributions, and from there into gravity field coefficients.

THEORETICAL BASIS and NUMERICAL IMPLEMENTATION:

The ocean responds to atmospheric forcings (wind, pressure, evaporation minus precipitation, radiation fluxes). The ocean's response can be divided in two classes: barotropic and baroclinic. The barotropic component has non-zero vertical-average (velocity, pressure, etc); the baroclinic component is the rest (e.g., Gill, 1982).

Generally speaking, barotropic motions are fast (fraction of a day to a few weeks), and baroclinic motions slow (weeks to centuries). The tides are the best example of barotropic motion, even though they include a little baroclinic energy in special places. El Niño is a predominantly baroclinic phenomenon.
A barotropic numerical ocean model ('barotropic model' in what follows) is one in which the whole water column has a single density; it is only forced by wind and pressure. A baroclinic model includes vertical density changes (as the real ocean has) and their effects, and requires the additional forcings (E-P, radiation, etc) to handle thermodynamic effects. The barotropic component in the real ocean (and in baroclinic models) can be the result of energy conversion from baroclinic modes and thus will not necessarily be the same as one obtained from a barotropic model. A barotropic model is simpler, has fewer dubious parameterizations, and runs faster on a computer than a baroclinic model.

Tierney et al (2000) showed that the difference between barotropic and baroclinic models in terms of sea surface height change was negligible in a global average (< 0.1 mm of seawater) for periods shorter than 100 days, and at those short periods only noticeable in some steep topography regions.

Barotropic model. For this algorithm we have chosen to run the barotropic model originally coded by R. Pacanowski, modified and described by Ponte (1991, 1997, 1999), then modified by Hirose et al (2000), and more recently by A. Ali at JPL. The code is dubbed 'PPHA' after its various authors.

The model is a finite-differences implementation of a simplification of the Navier-Stokes equations for shallow water (thin shell) and constant vertical density. The equations it satisfies (modified from Ponte et al, 1991) with wind and pressure forcing are:

$$d_t u - 2\Omega v . \sin(\varphi) - \frac{uv . \tan(\varphi)}{a} = -\frac{g}{a . \cos(\varphi)} \partial_\lambda \left(\zeta + \frac{p_a}{\varrho g} \right) - b\frac{u}{H} + \frac{\tau_\lambda}{\rho H} \qquad (1a)$$

$$d_t v + 2\Omega u . \sin(\varphi) + \frac{u^2 . \tan(\varphi)}{a} = -\frac{g}{a . \cos(\varphi)} \partial_\varphi \left(\zeta + \frac{p_a}{\varrho g} \right) - b\frac{v}{H} + \frac{\tau_\varphi}{\rho H} \qquad (1b)$$

$$\partial_t \varsigma + \frac{1}{a.\cos(\varphi)} \left\{ \partial_\lambda \left[(H+\zeta)u \right] + \partial_\varphi \left[(H+\zeta)v.\cos(\varphi) \right] \right\} = 0 \qquad (1c)$$

with d_t given by

$$d_t = \partial_t + \frac{u}{r.\cos(\varphi)} \partial_\lambda + \frac{v}{a} \partial_\varphi = 0 \qquad (2)$$

where λ, φ are longitude and latitude; $\partial_t, \partial_\lambda, \partial_\varphi$ are partial derivatives with respect to time, longitude or latitude; u, v are the eastward and northward components of velocity; ζ is the sea level departure from rest; H is the depth of the sea floor to sea level at rest; p_a is atmospheric surface pressure; τ_λ, τ_ϕ are the eastward and northward components of wind stress; ρ is the density of seawater, assumed a constant 1040 kg m^{-3}; g is the Earth's gravity acceleration, assumed a constant 9.806 m s^{-2}; Ω and a are the Earth's angular velocity and average radius, both assumed constant. A generalized no-slip boundary conditions is applied on the side and bottom bathymetry boundaries (Hirose et al, 2001). The numerical implementation involves choices of differencing scheme (Arakawa c-grid), integration scheme (leapfrog), and many other important numerical details (Ponte et al., 1991; Ponte, 1997).

The specific parameters used in the integration are:

- Resolution: 1.125° x 1.125° in longitude and latitude
- Time step: 1 minute
- Coverage: global, 75°S to 65°N
- subsurface no-slip condition of Hirose et al (2001)
- fine topography: a 1.125deg average of ETOPO5. Depths greater than 6000, are set to 6000m to allow for the 1 min time step. Depths shallower than 50m are set to the land flag.
- optimized Rayleigh friction parameter: -bu/H, b=2 cm/s, from the fit to TOPEX data.
- forced by wind stress and sea level pressure from either ECMWF or NCEP models (see below, 'inputs').

Wind stress. The model requires **wind stress** at the surface as input. ECMWF and NCEP do no make this parameter available in operational models. Rather, they have wind at various pressure levels (1000 mbar is the lowest), and through a PBL (planetary boundary layer) model, they convert these to 10 m wind (wind 10 m above the surface). This 10 m wind needs to be converted to a wind **stress** before it can be used to force the model.

$$\tau = C_d(|\mathbf{U}|)\mathbf{U}|\mathbf{U}| \qquad (3)$$

where τ is the surface wind stress vector, **U** is the horizontal wind vector 10 m above the ocean surface (from ECMWF or NCEP), || denotes magnitude, and C_d is a drag 'coefficient' with a weak dependence on the magnitude of **U** itself, as well as the stability of the boundary layer above the ocean. The conversion of wind to stress uses the stability-dependent formulation of Liu et al. (1979), discussed in Ali and Zlotnicki (2003)

Spinup. The model needs to be run with real wind and pressure forcing for at least 4 model months before operational output is desired, so as to minimize the effect of spinup transients. The code we use can be restarted from the model state of the last run so the spinup does not need to be rerun. Since we have been running it for 9+ model years at JPL, this is not a problem.

Sea Level, Ocean Bottom Pressure. The output of the finite-difference code is barotropic sea level in cm, and includes the effects of both wind and pressure forcing, so no assumption about 'inverted barometer' needs to be made. The above parameters and their effect on matching the model's output sea level to TOPEX/POSEIDON data are described in Hirose et al (2001) and in Ali et al (2000).

The sum of the model's output, multiplied by ρg to convert it to pressure in mbar, plus the atmospheric pressure at each grid point, is the pressure at the ocean's bottom, a quantity measured by bottom pressure recorders (although these are few and scattered, we have used them to spot-check the model's output).

$$p_B = p_A + \rho g \zeta + \rho g H = p_A + (1.004 \text{ mbar/cm\_seawater})(\zeta + H) \qquad (4)$$

where p_A is atmospheric pressure at sea level, p_B is ocean bottom pressure, ζ is the model's sealeavel (time-varying), H is the depth (time-invariant). All variables except ρg are functions of latitude and longitude. 1.004 mbar/cm_seawater assumes (a) that seawater density $\rho = 1.040$ g/cm^3; (b) that g=9.806 m/s^2. This 'ocean bottom pressure' quantity is the exact equivalent of atmospheric surface pressure over land (the overall 'weight' of the ocean and atmosphere above). If we used surface atmospheric pressure to dealias GRACE over land, then equation (4) would be used over the oceans.

Loading. This algorithm computes sea level relative to the ocean floor ($\zeta + H$). It performs no spherical harmonic decomposition, and does not correct for elastic loading. It is expected that the output of this model be combined with the atmospheric output before Love loading coefficients are applied.

Time-mean. As pointed out by T. Gruber, it is necessary to remove a time-mean value from the atmospheric and oceanic fields to avoid several problems. Per email of S. Bettadpur (15 Oct 2001) we have agreed to remove a simple 1 year time-mean from both ocean and atmosphere, and maintain it fixed at least for the first year of GRACE. Note that sealevel ζ is defined as departure from *rest,* not from the time mean. It does have a time-mean circulation in it.

Output Filter. As opposed to atmospheric pressure from ECMWF or NCEP, which is reasonably accurate over both short and long periods, this model and its output, ζ, are known to be inaccurate at periods longer than 120 days or so, because of the barotropic approximation. However, the output does have energy at these longer periods because the wind and pressure forcing themselves change over long periods. Therefore it is necessary to filter out these incorrect, long period components from the output to avoid misinterpreting the resulting GRACE data.

This simple procedure has been agreed to for GRACE dealiasing: no time or frequency filter will be applied to the output of the ocean model. After the monthly-averaged gravity fields are computed and before being interpreted over the oceans (this is outside the GRACE ground system), they shall be converted to surface mass density anomalies expressed as cm of water height, and the monthly averaged ocean model output in terms of water height (which was removed from the GRACE data by the level 2 processing), shall be added back.

INPUT DATA:

Time varying:

- The end state output by the previous model run, which is used as initial state of the current run.
- tpemrun.inp, a parameter file output in the previous model run, and described in a separate readme file.

- Gridded U,V Wind (N and E) components, at 10m height
- Gridded Pressure at Sea Level.

Both the U,V wind and the P pressure are expected on a 1.125 degree grid, in GDF (Gitter Daten Format), at 00, 06, 12, 18 hours. As explained in previous sections, these fields are from the European Center for Medium Range Weather Forecast and have been acquired at GFZ as part of the GRACE ground system as described in previous sections.

Time invariant:

- whether the input is ECWMF or NCEP
- friction coefficient
- bathymetry file, interpolated to model grid
- a flag to indicate whether Kondo or LKB wind to stress conversion should be used.

PROCESSING STEPS:

The steps related to obtaining the ECMWF files, changing their format, resampling them to the 1.125 grid, etc. have been described in an earlier section.

As delivered to GFZ, the JPL executable completes two distinct steps internally:

Step 1: convert wind vector to wind stress using LKB algorithm, and outputs them in a format used in the next step

Step 2: restarts barotropic model from last saved state (24 hours earlier), and runs for 24 hours or longer, saving 1/hour grids. On termination, the last model state and last forcing fields are saved.

Processing time on a Cray J90 (nebula at JPL in 2001). is approx. 4 hrs per 6 month model run. A SUN ULTRA10 correctly ran at the rate of 1 model day in under 30 minutes (note that both are obsolete computers in 2003; the timing runs were performed in 2001)

OUTPUT:

The output includes the following files:

tpemrun_end.res: final model state and input to the next run

tpemrun.sl: total sea level height, from rest, in cm, at the grid node positions..

tpemrun_sl.Header: ASCII header file describes the .sl file

Only the four files are useful to the GRACE processing.

The other files, which are output are:

tpemrun.ibd: sea level minus inverted barometer
tpemrun.tpa: global average atmosphere pressure
tpemrun.u: east water velocity
tpemrun.v: north water velocity

NOTE: The tpemrun.sl output file is renamed by GFZ's scripts as pressol.yyyymmdd.DAT, where yyyy is the year mm the month and dd the day (see figure 3-1)

Model output is packed into 1-day files, 24 grids per file. Each file is under 4 MB/day, including header information.

INTERFACE:

- GFZ shall deliver periodically the pressol.yyyymmdd files, and their associated tpemrun.tpa, .u and .v files for JPL/Oceans to perfom continuous testing and possibly model improvements, including the computation of Earth rotation components from the output.

- GFZ shall report to JPL/Oceans (V. Zlotnicki) any problems encountered in execution. JPL/Oceans shall be responsible for prompt correction, recompilation, and delivery of a corrected executable to GFZ.

- JPL/Oceans shall inspect the output pressol files on a routine basis and in a timely manner, and inform GFZ promptly of any problems encountered. JPL/Oceans shall fix such problems to the extent they are not caused by the external inputs.

ERROR ANALYSIS:
TBD

KNOWN PROBLEMS/LIENS/RESTRICTIONS:

1) Although the model has a Mediterranean sea, Hudson Bay, North Sea, and shallow waters, the model's performance in these enclosed or shallow areas, is not as good as in the deep, open ocean, as measured by variance reduction in the TOPEX/POSEIDON data. This is of special concern for the Mediterranean. This may hurt LAND estimates of gravity as the nearby ocean aliasing is improperly accounted for.

2) Model does not reproduce baroclinic behaviour, which begins to compensate barotropic mass anomalies for periods > ~100 days. This must simply be kept in mind.

Proposed handling: use full model output to 'correct' sat-sat tracking data, then after monthly gravity field is computed, remove the barotropic monthly-mean surface mass distribution from the gravity field solution (of course, both in the same terms: either gravity or surface mass distributions).

3) Model does not currently include gravitational self-attraction. A recent estimate by Hughes et al TBD

4) Model does not include mass additions due to river inflow, nor mass fluxes at the surface due to precipitation minus evaporation, nor mass exchange at high latitude due to freezing or thawing.

COMMENTS:
TBD

CREDITS:
All the design, coding and testing of this algorithm package was performed by Dr. Ahmed H. Ali, of Raytheon ITSS, in collaboration with Dr. V. Zlotnicki, JPL/Oceans.

REFERENCES:
See chapter 6 (References on Barotropic Model)

3   Processing Strategy for the Atmosphere and the Ocean

In this chapter the processing strategy for the ocean and the atmosphere is described. Additionally, the corresponding mean fields which are necessary for the calculation of residual pressure values are defined. Finally, the combination of the ocean and the atmosphere is explained.

3.1   *Processing Strategy Ocean*

The following figure describes the processing strategy to run the barotropic ocean model (see chapter 2.2) to generate barotropic sea level
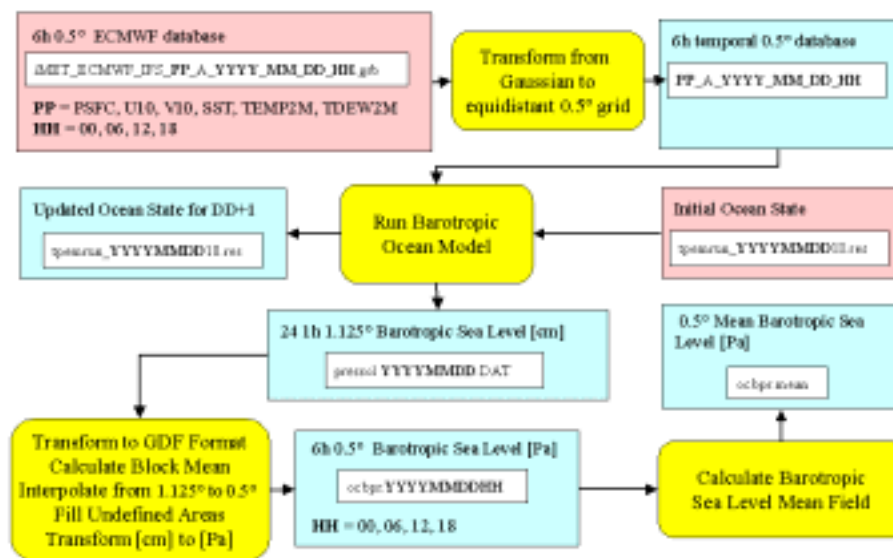

Figure 3-1: Processing Strategy Ocean (red: input, yellow: processing step, light blue: output)

- Input data are the following 6 hourly ECMWF atmospheric fields (see chapter 2.1)
    - IMET_ECMWF_IFS_PSFC_A_YYYY_MM_DD_HH.grb: surface pressure
    - IMET_ECMWF_IFS_U10_A_YYYY_MM_DD_HH.grb: U wind speed
    - IMET_ECMWF_IFS_V10_A_YYYY_MM_DD_HH.grb: V wind speed
    - IMET_ECMWF_IFS_SST_A_YYYY_MM_DD_HH.grb: sea surface temperature
    - IMET_ECMWF_IFS_TEMP2M_A_YYYY_MM_DD_HH.grb: temperature at 2 m level
    - IMET_ECMWF_IFS_TDEW2M_A_YYYY_MM_DD_HH.grb: dew point temperature at 2 m level
  and an initial ocean model state "tpemrun_YYYYMMDD18.res" which has been provided by JPL for July 1, 2000
- The ECMWF data are transformed from a 0.5° gaussian grid to a 0.5° equidistant grid. This temporal ECMWF data base and the initial ocean model state force the ocean model. As a result 24 1 hourly 1.125° barotropic sea level states are produced by the ocean model represented in one binary file "pressol.YYYYMMDD.DAT". Additionally the ocean model state to initiate the next day´s run is calculated.
- For the later combination with the atmosphere the epochs at 0, 6, 12 and 18 hours are extracted, transformed to an internal GDF (grid data format) format and interpolated to 0.5° block mean values. Also the output unit [cm] is transformed to [Pa] using the constant gravity value and salt water density of the ocean model. Undefined ocean areas (generally above +65° and below -75° latitude) are filled with 0. As a result every day 4 files "ocbpr.YYYYMMDDHH" with barotropic sea level [Pa] are available.

- This "ocbpr files" have been used to calculate an ocean model mean field (see chapter 3.3) which is necessary to derive residual barotropic sea level (see chapter 3.4) for individual days.

The processing time for a 1 model day on a SUN Ultra 450 using one (out of 4) 400 MHz CPU is 18 minutes.

3.2 Processing Strategy Atmosphere

To take into account the atmospheric mass variations for the calculation of the de-aliasing product two different methods have been coded: The surface pressure (SP) and the vertical integration (VI) approach. Both are described in the following chapters.

3.2.1 Surface Pressure

3.2.1.1 Fundamental Formulas

Surface pressure data can be easily transformed into gravity harmonics by spherical harmonic analysis with integration and by applying specific factors for re-scaling the spherical harmonic coefficients. The gravitational potential V at a point outside the Earth due to heterogeneous mass distribution inside the Earth is expressed by a spherical harmonic expansion using normalized coefficients C_{nm} and S_{nm} of degree n and order m (Heiskanen and Moritz, 1967, 2-34, 2-35 with 2-40).

$$V = \frac{kM}{r} \sum_{n=0}^{\infty} \sum_{m=0}^{n} \left(\frac{a}{r}\right)^n P_{nm}(\cos\theta)\left(C_{nm}\cos m\lambda + S_{nm}\sin m\lambda\right) \tag{3-1}$$

$$C_{nm} = \frac{1}{(2n+1)Ma^n} \iiint_{Earth} r^n P_{nm}(\cos\theta)\cos m\lambda\, dM$$

$$S_{nm} = \frac{1}{(2n+1)Ma^n} \iiint_{Earth} r^n P_{nm}(\cos\theta)\sin m\lambda\, dM \tag{3-2}$$

with the mass, volume or surface elements:

$$dM = \rho\, dV = \rho r^2 dr \sin\theta\, d\theta\, d\lambda = r^2 q \sin\theta\, d\theta\, d\lambda = r^2 q\, dS \tag{3-3}$$

k	Gravity constant
a	Radius of sphere
M	Earth mass
P_{nm}	Associated Legendre polynomials (normalized)
(r,θ,λ)	Spherical coordinates of mass element
dM	Mass element
dV	Volume element
ρ	Density
q	Surface load (mass per surface)
dS	Surface element

Introducing volume elements, it can be seen that the density distribution becomes a factor in the integral over the complete Earth. Density variations mainly occur in the hydrosphere (atmosphere and oceans) and acts as a variable loading effect on the solid Earth surface (Gegout and Cazenave, 1993). Surface loads are represented as mass per surface element q. Because we are on the Earth surface the variable radius r can be set to the spherical radius a. Then, the coefficients are determined by:

$$C_{nm} = \frac{a^2}{(2n+1)M} \iint_{Earth} q P_{nm}(\cos\theta) \cos m\lambda\, dS$$

$$S_{nm} = \frac{a^2}{(2n+1)M} \iint_{Earth} q P_{nm}(\cos\theta) \sin m\lambda\, dS$$

(3-4)

The surface load is defined by:

$$q = \frac{P_S}{g} = \rho_W h$$

(3-5)

where
P_S Surface pressure
G   Mean gravity acceleration
ρ_W Density of water (salt water 1040, continental water 1000 kg/m^3)
h   Height of water column (1mm = 1kg/m^2)

Introducing the surface pressure the gravity coefficients are determined by:

$$C_{nm} = \frac{a^2}{(2n+1)Mg} \iint_{Earth} P_S P_{nm}(\cos\theta) \cos m\lambda\, dS$$

$$S_{nm} = \frac{a^2}{(2n+1)Mg} \iint_{Earth} P_S P_{nm}(\cos\theta) \sin m\lambda\, dS$$

(3-6)

Taking into account the elastic deformation of the solid Earth under the variable load via the load Love number k_n for loading harmonic of degree n we get the final formula:

$$C_{nm} = \frac{a^2(1+k_n)}{(2n+1)Mg} \iint_{Earth} P_S P_{nm}(\cos\theta) \cos m\lambda\, dS$$

$$S_{nm} = \frac{a^2(1+k_n)}{(2n+1)Mg} \iint_{Earth} P_S P_{nm}(\cos\theta) \sin m\lambda\, dS$$

(3-7)

Because in the current approach the de-aliasing product is represented by a spherical harmonic series of degree and order 100 the following loading Love numbers are used (Dong et al, 1996, Farrel, 1972):

$$k_0 = 0; \quad k_1 = 0; \quad k_2 = -0.308; \; k_3 = -0.195; \; k_4 = -0.132$$
$$k_5 = -0.103; \; k_6 = -0.089; \; k_7 = -0.082; \; k_8 = -0.078; \; k_9 = -0.073$$

$$\text{for } k_{10} \text{ to } k_{17}: \quad -\frac{0.682 + 0.27(n-10)/8}{n}$$

$$\text{for } k_{18} \text{ to } k_{31}: \quad -\frac{0.952 + 0.288(n-18)/14}{n}$$

$$\text{for } k_{32} \text{ to } k_{55}: \quad -\frac{1.24 + 0.162(n-32)/24}{n}$$

$$\text{for } k_{56} \text{ to } k_{100}: \quad -\frac{1.402 + 0.059(n-56)/44}{n}$$

3.2.1.2 Processing Sequence

Starting point are point values of surface pressure on a regular equiangular grid. Before numerical integration the point values have to be transformed to block-mean values representing the pressure for the block. As for the point values, blocks are defined on an equiangular grid. To analyze gravity variations caused by atmospheric surface pressure variations a mean surface pressure field covering at least one year of data has to be subtracted (in order to eliminate seasonal effects in the mean field) in above equation 3-7 (see also chapter 3.3). After subtraction of the mean pressure field residual pressure data, which represent mass variations with respect to the mean field are available.

$$C_{nm} = \frac{a^2(1+k_n)}{(2n+1)Mg} \iint_{Earth} (P_S - \overline{P}_S) P_{nm}(\cos\theta) \cos m\lambda \, dS$$

$$S_{nm} = \frac{a^2(1+k_n)}{(2n+1)Mg} \iint_{Earth} (P_S - \overline{P}_S) P_{nm}(\cos\theta) \sin m\lambda \, dS$$

(3-8)

Then numerical integration starts row by row computing the integrals of associated Legendre polynomials in latitude direction and integrals of trigonometric functions in longitude direction. After completion the residual gravity spherical harmonic series is available. This gravity series corresponds to the deviation of the gravity field from the mean gravity field due to atmospheric mass variations.

3.2.2 Vertical Integration of Atmospheric Column

3.2.2.1 Fundamental Formulas

If the vertical structure of the atmosphere shall be taken into consideration the vertical integration of the atmospheric masses has to be performed. For this case we start again with the basic formulas (3-1) and (3-2) from chapter 3.2.1 and introduce the volume elements defined in formula (3-3).

$$C_{nm} = \frac{1}{(2n+1)Ma^n} \iint_{Earth} \left[\int_0^\infty r^{n+2} \rho \, dr \right] P_{nm}(\cos\theta) \cos m\lambda \sin\theta \, d\theta \, d\lambda$$

$$S_{nm} = \frac{1}{(2n+1)Ma^n} \iint_{Earth} \left[\int_0^\infty r^{n+2} \rho \, dr \right] P_{nm}(\cos\theta) \sin m\lambda \sin\theta \, d\theta \, d\lambda$$

(3-9)

Using the hydrostatic equation:

$$\rho \, dr = -\frac{dP}{g_r}$$

(3-10)

we get:

$$C_{nm} = -\frac{1}{(2n+1)Ma^n} \iint_{Earth} \left[\int_{P_S}^0 \frac{r^{n+2}}{g_r} dP \right] P_{nm}(\cos\theta) \cos m\lambda \sin\theta \, d\theta \, d\lambda$$

$$S_{nm} = -\frac{1}{(2n+1)Ma^n} \iint_{Earth} \left[\int_{P_S}^0 \frac{r^{n+2}}{g_r} dP \right] P_{nm}(\cos\theta) \sin m\lambda \sin\theta \, d\theta \, d\lambda$$

(3-11)

The gravity acceleration in height r (g_r) can be approximated from the mean gravity acceleration g by:

$$g_r = g \left(\frac{a}{r} \right)^2$$

(3-12)

Then we get:

$$C_{nm} = -\frac{1}{(2n+1)M a^{n+2} g} \iint\limits_{Earth} \left[\int\limits_{P_S}^{0} r^{n+4} dP \right] P_{nm}(\cos\theta)\cos m\lambda \sin\theta d\theta d\lambda$$

$$S_{nm} = -\frac{1}{(2n+1)M a^{n+2} g} \iint\limits_{Earth} \left[\int\limits_{P_S}^{0} r^{n+4} dP \right] P_{nm}(\cos\theta)\sin m\lambda \sin\theta d\theta d\lambda$$

(3-13)

The radial coordinate r is composed of (see figure 3-2 and (Wahr and Svensson, 1999)):

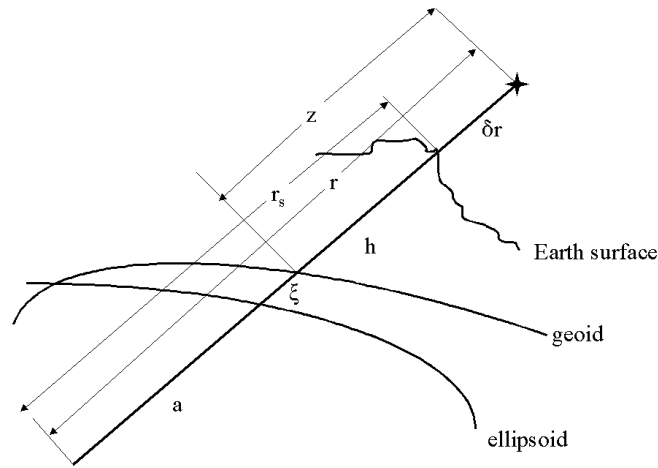$$r = r_s + \delta r = a + \xi + h + \delta r = a + \xi + z \tag{3-14}$$

Figure 3-2: Radial component r used in vertical integration

ξ is the height of the mean geoid above the mean sphere r = a., h is the elevation of the Earth´s surface above the mean geoid (Earth´s surface topography). The geopotential height ϕ at a point * above the Earth´s surface r = a + z is defined by:

$$\Phi = \frac{1}{g} \int\limits_{0}^{z} g_r dz = a\left(\frac{z}{a+z}\right) \tag{3-15}$$

After transformation we get:

$$\Phi = a\left(\frac{z}{a+z}\right) \Rightarrow \frac{\Phi}{a} = \frac{z}{a+z} \Rightarrow z = \frac{(a+z)\Phi}{a} \Rightarrow z = \frac{\Phi a}{a} + \frac{\Phi z}{a} \Rightarrow$$

$$\Phi = z - \frac{\Phi z}{a} \Rightarrow \Phi = z\left(1 - \frac{\Phi}{a}\right) \Rightarrow z = \frac{\Phi}{\left(1 - \frac{\Phi}{a}\right)}$$

(3-16)

Then it follows:

$$r = a + \frac{\Phi}{\left(1 - \frac{\Phi}{a}\right)} + \xi = \frac{a\left(1 - \frac{\Phi}{a}\right) + \Phi}{\left(1 - \frac{\Phi}{a}\right)} + \xi = \frac{a}{\left(1 - \frac{\Phi}{a}\right)} + \xi \tag{3-17}$$

This expression is substituted in (3-13):

$$C_{nm} = -\frac{1}{(2n+1)Ma^{n+2}g} \iint_{Earth} \left[\int_{P_S}^{0} \left(\frac{a}{1-\frac{\Phi}{a}} + \xi \right)^{n+4} dP \right] P_{nm}(\cos\theta)\cos m\lambda \sin\theta d\theta d\lambda$$

$$S_{nm} = -\frac{1}{(2n+1)Ma^{n+2}g} \iint_{Earth} \left[\int_{P_S}^{0} \left(\frac{a}{1-\frac{\Phi}{a}} + \xi \right)^{n+4} dP \right] P_{nm}(\cos\theta)\sin m\lambda \sin\theta d\theta d\lambda$$

(3-18)

After including the degree dependent term into the integral (for numerical reasons) and introducing again the elastic deformation of the solid Earth (see equation 3-7) we get the following final formulas for determination of the gravity coefficients using the vertical integration approach:

$$C_{nm} = -\frac{a^2(1+k_n)}{(2n+1)Mg} \iint_{Earth} \left[\int_{P_S}^{0} \left(\frac{a}{a-\Phi} + \frac{\xi}{a} \right)^{n+4} dP \right] P_{nm}(\cos\theta)\cos m\lambda \sin\theta d\theta d\lambda$$

$$S_{nm} = -\frac{a^2(1+k_n)}{(2n+1)Mg} \iint_{Earth} \left[\int_{P_S}^{0} \left(\frac{a}{a-\Phi} + \frac{\xi}{a} \right)^{n+4} dP \right] P_{nm}(\cos\theta)\sin m\lambda \sin\theta d\theta d\lambda$$

(3-19)

From the meteorological analysis centers usually not the geopotential height ϕ, but temperature and specific humidity are available on the model or half levels. Therefore, before the integration with formula (3-19) can be performed numerically, the geopotential heights for all levels have to be computed. This computation can be done in the following way (White, 2001, formula 2.21; Schrodin 2000, page 51) (N_{Level} represents the lowest level).

$$\Phi_{k+1/2} = \Phi_S + \frac{1}{g} \sum_{j=k+1}^{N_{level}} R_{dry} T_v \ln \frac{P_{j+1/2}}{P_{j-1/2}}$$

(3-20)

with $\phi_{k+1/2}$ Geopotential height at half level (layer interfaces)

ϕ_S Geopotential height at surface (if provided as potential divide by

g_0)

R_{dry} Gas constant for dry air = 287 m²/s²K = 287 J/kgK
T_v Virtual temperature
$P_{k+1/2}$ Pressure at half level (layer interface)

$$T_v = (1 + 0.608 S)T$$

(3-21)

S   Specific humidity
T   Temperature

$$P_{k+1/2} = a_{k+1/2} + b_{k+1/2} P_S$$

(3-22)

$a_{k+1/2}$ Model dependent coefficient
$b_{k+1/2}$ Model dependent coefficient
Both coefficients are provided in ECMWF GRIB files, for DWD see Schroding 2000, p.51)

The geopotential heights at pressure levels finally can be used to compute the inner integral in (3-19). In the second term ξ/a the mean geoid above the sphere r=a can be approximated by the geopotential height at the Earth´s surface (orography) which is available at ECMWF.

3.2.2.2 Processing Sequence

Starting points are point values of surface pressure and geopotential height grids on the Earth's surface and point values of temperature and specific humidity at all model levels of the atmospheric model in the same global grid. All these equiangular point grids are transformed to block mean grids by applying a mean value operator to the 4 corner points. Then the pressure at all model levels (formula 3-22) is computed by using the atmospheric model specific interpolation coefficients (a, b). These pressure values, the virtual temperature, which is computed from the real temperature and the specific humidity in each model level (3-21) and the surface geopotential heights are used to compute the geopotential heights for all levels. For this also a mean gravity acceleration has to be used, which is computed from the reference ellipsoid WGS84. In our case the normal gravity at the equator is used. Then the integration is done numerically for each degree separately using the geopotential heights of the model levels. These intermediate results are stored in a three dimensional array with longitude, latitude and degree as indices. Finally the spherical harmonic analysis is performed for each degree of the spherical harmonic series separately, in order to take into account the degree dependent exponent in equation (3-19). Finally the complete spherical harmonic series is written on a binary spherical harmonic series file.

To analyze gravity variations caused by atmospheric vertical integrated pressure variations a corresponding mean field covering at least one year of data has to be subtracted (in order to eliminate seasonal effects in the mean field) from the inner integral of above equation 3-19 (see also chapter 3.3). After subtraction of the mean pressure field residual pressure data, which represent mass variations with respect to the mean field are available:

$$C_{nm} = -\frac{a^2\left(1+k_n\right)}{(2n+1)Mg} \iint_{Earth} \left(\left[\int_{P_S}^{0}\left(\frac{a}{a-\Phi}+\frac{\zeta}{a}\right)^{n+4} dP\right] - \overline{P}_{VI}\right) P_{nm}(\cos\theta)\cos m\lambda \sin\theta d\theta d\lambda$$

$$S_{nm} = -\frac{a^2\left(1+k_n\right)}{(2n+1)Mg} \iint_{Earth} \left(\left[\int_{P_S}^{0}\left(\frac{a}{a-\Phi}+\frac{\zeta}{a}\right)^{n+4} dP\right] - \overline{P}_{VI}\right) P_{nm}(\cos\theta)\sin m\lambda \sin\theta d\theta d\lambda$$

(3-23)

For a better clarification of this processing sequence a pseudo code is provided below.

Read global surface pressure from GRIB file
        IMET_ECMWF_IFS_PSFC_A_YYYY_MM_DD_HH.grb
Read global surface geopotent. height from GRIB file
        IMET_ECMWF_IFS_PHISFC_A_YYYY_MM_DD_HH.grb
Read global model level temperatures from GRIB file
        IMET_ECMWF_IFS_TEMP_A_YYYY_MM_DD_HH.grb
Read global model level specific humidity from GRIB file
        IMET_ECMWF_IFS_SHUM_A_YYYY_MM_DD_HH.grb
Compute for all global data sets block mean values
Do for all block means in the global grid files
        Do for all model levels
                Compute pressure at model level (3-22)
                Compute virtual temperature a model level (3-21)
                Compute geopotential height of model level by summing up individual heights and
                    add surface geopotential height (3-20)
                Compute expression in large brackets of inner integral in (3-19)
                Do for all degrees of spherical harmonic series
                        Apply exponent and do numerical integration by multiplication with pressure
                            difference of model levels and summation of all model levels
                      Store result in temporary 3-D field with long., latitude and degree as indices
                End Do
        End Do
End Do

Do for all degrees of spherical harmonic series
      Subtract mean contribution for this degree by reading it from a separate file
      Perform spherical harmonic analysis for this degree using the temporary 3-D field (3-19)
      Store coefficients of this degree in result vector
End Do
Write spherical harmonic series to output file

The processing time for a 1 day processing on a SUN Ultra 450 using one (out of 4) 400 MHz CPU is approximately 2 hours.

3.3 Mean Ocean and Atmospheric Pressure Fields

To calculate residual barotropic sea level or residual atmospheric pressure fields (see equation 3-8 for surface pressure resp. equation 3-23 for vertical integration) corresponding mean fields have been computed for 2001. This mean fields are shown below.
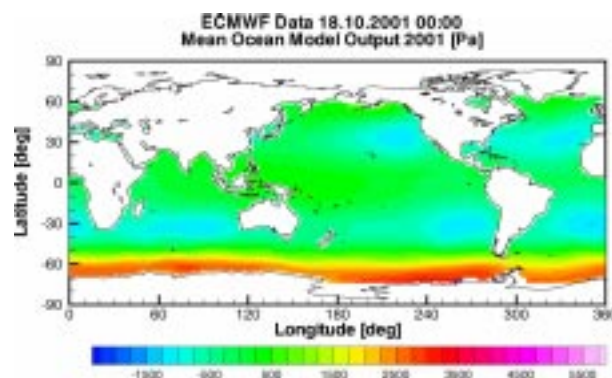

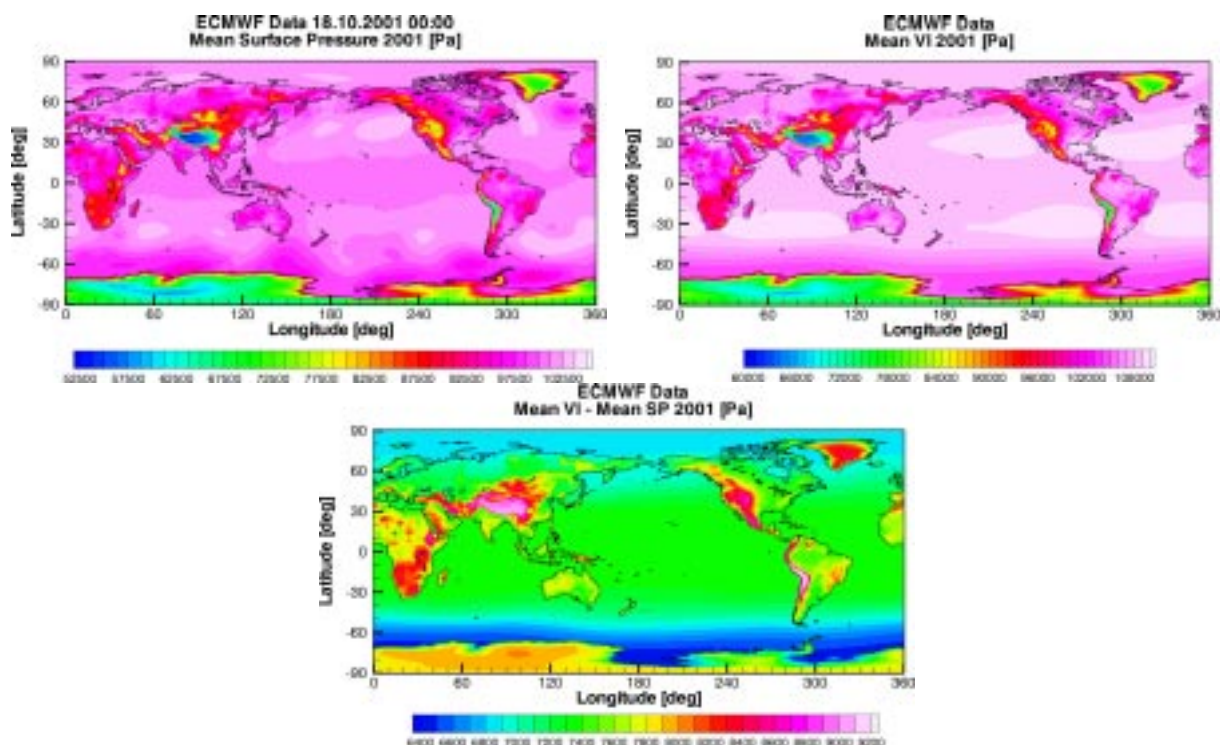**Figure 3-3:** Barotopic sea level mean field [Pa] for 2001

Figure 3-4: Surface pressure (upper left) and vertical integrated mean field for 2001 [Pa] (upper right) and their difference (lower middle) [Pa]

The bias of about 7000 Pascal between the surface and vertical integrated mean fields is due to the different mean heights.

3.4 Combination of Atmosphere and Ocean

To get the global residual pressure field, used as input for calculation of the spherical harmonic series, the ocean and atmosphere actual and mean fields are combined in the following way (example see figure 3-5):

1. Build the difference between the actual 6h barotropic sea level (chapter 3.1) and the mean barotropic sea level (chapter 3.3) which defines the residual barotropic sea level (see figure 3-6)
2. Undefined ocean areas (e.g. ocean areas above 65° and -75° latitude) are filled with 0
3. Build the difference between the actual 6h surface or vertical integrated pressure (chapter 3.2) and the atmospheric mean field (chapter 3.3) which defines the residual atmospheric pressure (example see figure 3-7)
4. Over the oceans the residual barotropic sea level and the residual atmospheric pressure are added
5. The land and ocean residual pressure values are the input to calculate spherical harmonic series, which are stored in an ASCII file (the AOD1B product, see chapter 5)
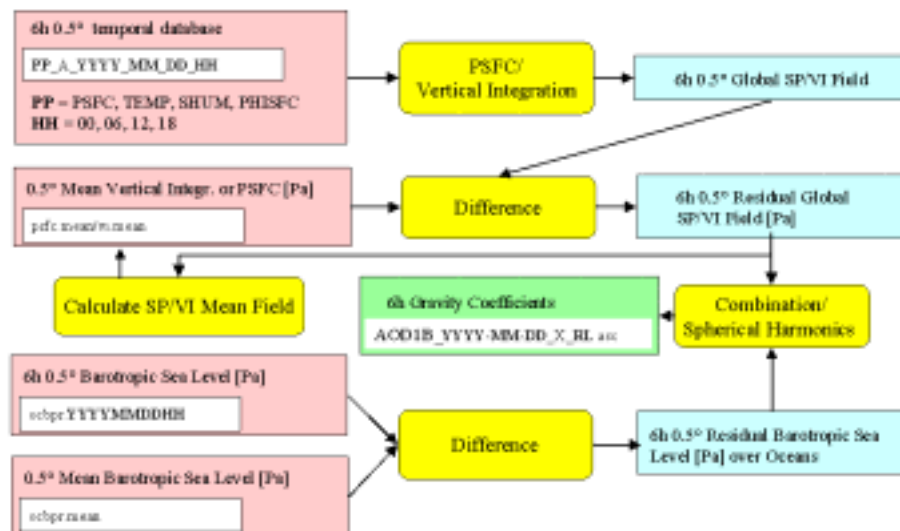
Figure 3-5: Processing strategy combination of ocean and atmosphere (red: input, yellow: processing step, light blue and green: output)
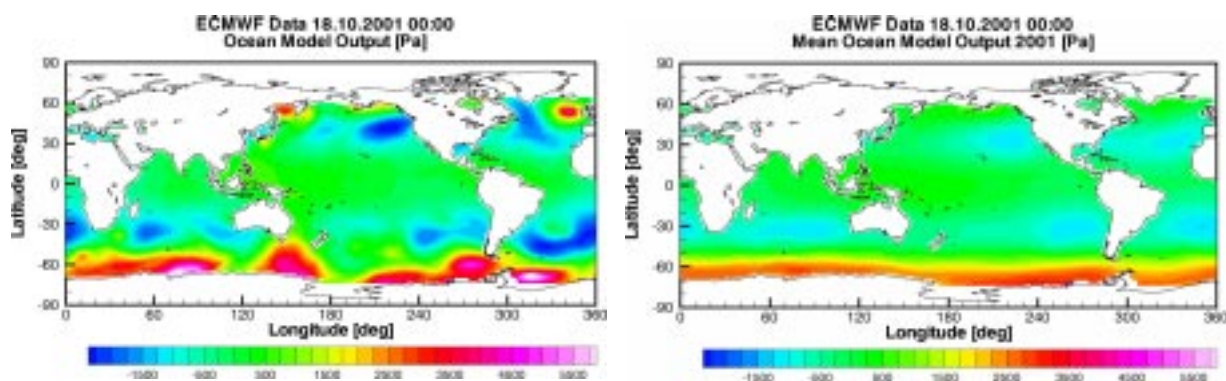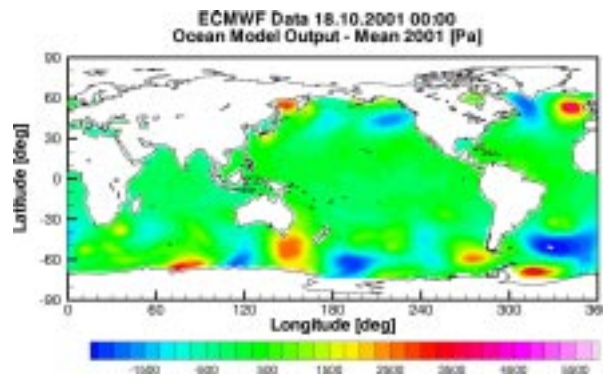
Figure 3-6: Barotopic sea level on October 18, 2001, 00:00 (upper left), 2001 mean field (upper right) and corresponding residual field (lower middle) [Pa]
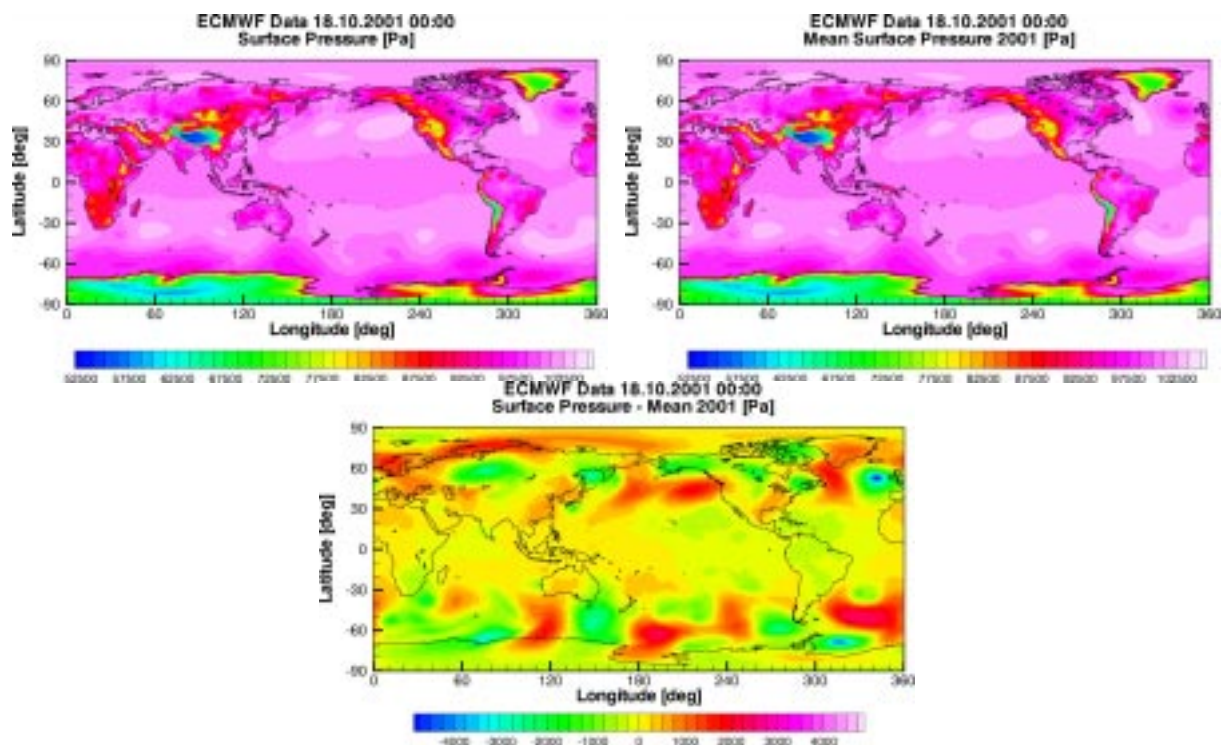
Figure 3-7: Surface pressure on October 18, 2001, 00:00 (upper left), 2001 mean field (upper right) and corresponding residual field (lower middle) [Pa]

4   Validation of the AOD1B Product

4.1   Geoid Height Variation Statistics

The 6-hourly residual pressure spherical harmonic coefficients (AOD1B product) are transformed to corresponding geoid height variations. The minimum, maximum, mean and rms values are used to check the AOD1B product on consistency. Minimum and maximum values are in the range of ±5-15 mm, the mean should be around 0 mm, the rms is usually around 2-5 mm. The following figure shows the corresponding monthly results for April to July 2002.
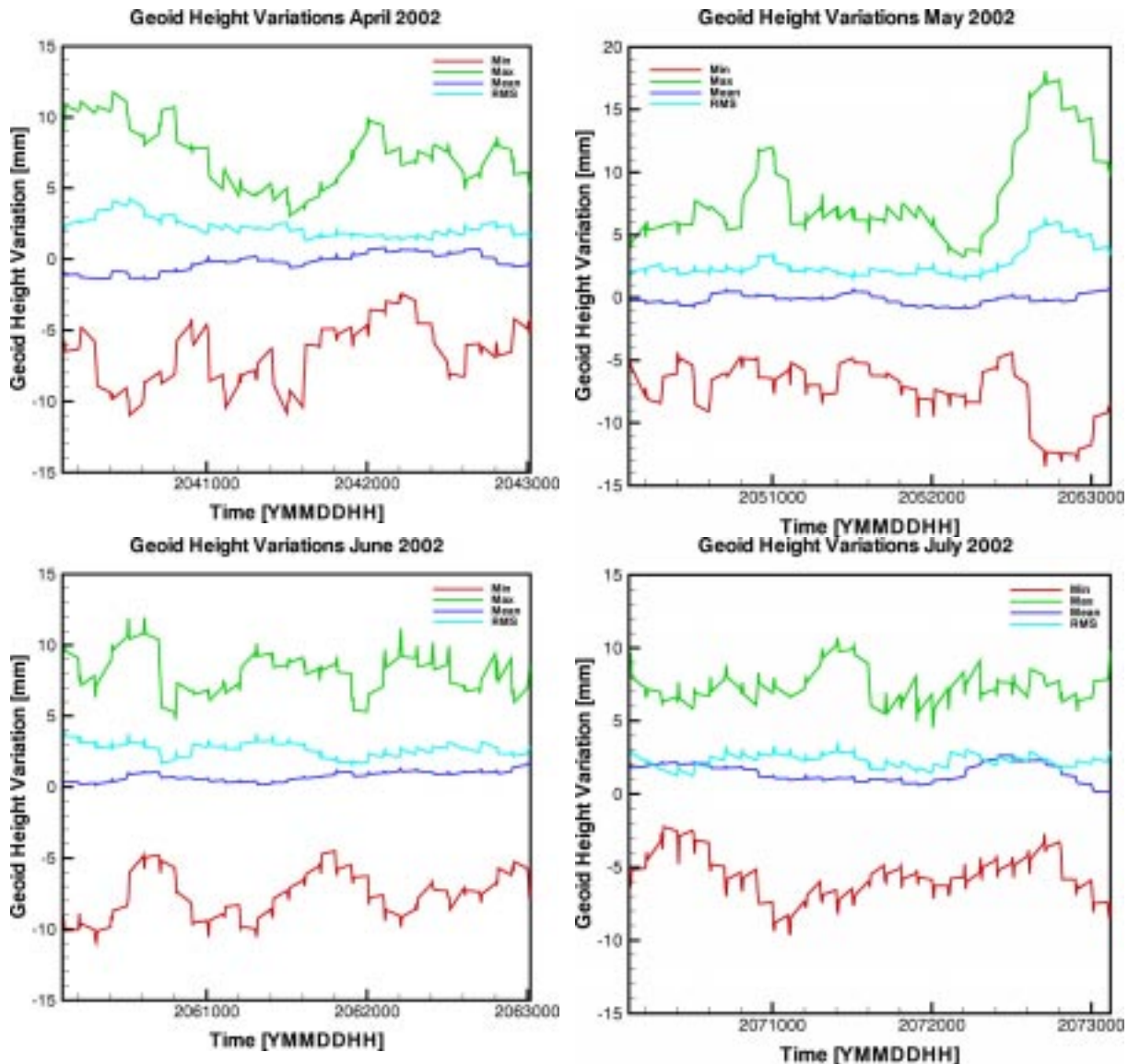
Figure 4-1: Geoid height variation statistics (minimum, maximum, mean and rms) for April to July 2002

The long-term statistic for July 1, 2000 (first AOD1B product available) until August 31, 2003 is shown in the following figure

Figure 4-2: Geoid height variation statistics (minimum, maximum, mean and rms) for July 1, 2000 until August 31, 2003
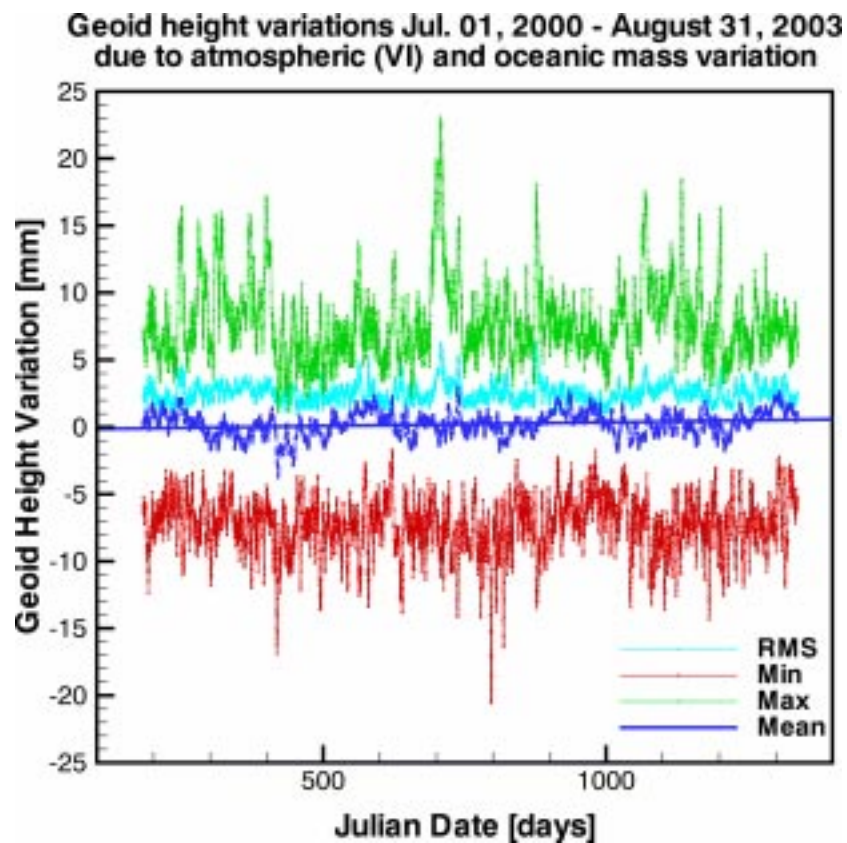
It is obvious that the long-term mean geoid height variation, represented by a linear fit (see blue line), is zero which proofs the overall de-aliasing concept.

5 AOD1B and OCN1B Format Description

In the following chapters the output format of the atmosphere and ocean de-aliasing product (AOD1B) and the ocean model output (OCN1B) are described.

5.1 Format of the Atmosphere and Ocean De-aliasing Product (AOD1B)

The AOD1B products will be available in the GRACE ISDC on a daily basis using the GRACE level-1 filename convention "AOD1B_YYYY-MM-DD_S_RL.EXT.gz" (Case *et al.*, 2002) where "YYYY-MM-DD" is the corresponding date, the GRACE satellite identifier "S" is fixed to X (meaning product cannot be referred to GRACE-A or GRACE-B), RL is an increasing release number and EXT is fixed to asc (ASCII data). For data transfer simplification the products are gnu-zipped (suffix "gz").

Each file consists of a header with a dedicated number of lines (NUMBER OF HEADER RECORDS) and ends with a constant header line (END OF HEADER). The first part of the header is based on the level-1 instrument product header convention (Case *et al.*, 2002) and gives more general information on the product (header lines PRODUCER AGENCY to PROCESS LEVEL). These lines are accomplished by a certain number of header lines describing the de-aliasing product more precisely like

```
PRESSURE TYPE (SP OR VI)       : Surface Pressure or Vertical Integration approach
MAXIMUM DEGREE                 : The maximum degree of the spherical harmonic series
COEFFICIENT ERRORS (YES/NO)    : Yes, if errors are added to the coefficients
COEFF. NORMALIZED (YES/NO)     : YES, if the coefficients are normalized
CONSTANT GM [M^3/S^2]          : GM value used for computation
CONSTANT A [M]                 : semi-major axis value used for computation
CONSTANT FLAT [-]              : flattening value used for computation
CONSTANT OMEGA [RAD/S]         : Earth rotation rate used for computation
NUMBER OF DATA SETS            : Number of data fields per product
DATA FORMAT (N,M,C,S)          : Format to read the data (depending on header line " COEFFICIENT
                                 ERRORS (YES/NO)"
```

The NUMBER OF DATA SETS is usually 12 because for each 6-hours 3 different spherical harmonic series are provided. Before calculation of the spherical harmonic series the 0.5º block means are defined as follows (also depending on PRESSURE TYPE (SP OR VI)):

1. DATA SET TYPE "glo" (global atmosphere and ocean combination):
Land: [SP-SP(mean)] or [VI-VI(mean)]
Defined ocean area: [ocean-ocean(mean) + SP-SP(mean)] or [ocean-ocean(mean) + VI-VI(mean)]
Undefined ocean area: 0

2. DATA SET TYPE "atm" (global atmosphere):
Land area: [SP-SP(mean)] or [VI-VI(mean)]
Defined ocean area: [SP-SP(mean)] or [VI-VI(mean)]
Undefined ocean area: [SP-SP(mean)] or [VI-VI(mean)]

3. DATA SET TYPE "ocn" (ocean area):
Land: 0
Defined ocean: ocean-ocean(mean)
Undefined ocean: 0

Note: Due to the undefined ocean pixels in the barotropic ocean model (pixels outside the 75°S/65°N latitude band) the sum of the "ocn" and "atm" coefficients is **not** the "glo" coefficient!

The following is an example for the AOD1B_2002-05-01_X_00.asc product, where for simplification only the two first and last coefficients of each data set are given:

```
PRODUCER AGENCY              : GFZ
PRODUCER INSTITUTION         : GFZ
FILE TYPE ipAOD1BF           : 999
FILE FORMAT 0=BINARY 1=ASCII : 1
NUMBER OF HEADER RECORDS     : 29
SOFTWARE VERSION             : atm_ocean_dealise.01
SOFTWARE LINK TIME           : Not Applicable
REFERENCE DOCUMENTATION      : GRACE De-aliasing ADD
SATELLITE NAME               : GRACE X
SENSOR NAME                  : Not Applicable
TIME EPOCH (GPS TIME)        : 2000-01-01 12:00:00
TIME FIRST OBS(SEC PAST EPOCH):  73483148.816000 (2002-04-30 23:59: 8.82)
TIME LAST OBS(SEC PAST EPOCH) :  73569548.816000 (2002-05-01 23:59: 8.82)
NUMBER OF DATA RECORDS       :     61812
PRODUCT CREATE START TIME(UTC): 2003-02-25 15:49:57.000
PRODUCT CREATE END TIME(UTC) : 2003-02-25 17:50:18.000
FILESIZE (BYTES)             :    2474676
FILENAME                     : AOD1B_2002-05-01_X_01.asc
PROCESS LEVEL (1A OR 1B)     : 1B
PRESSURE TYPE (SP OR VI)     : VI
MAXIMUM DEGREE               : 100
COEFFICIENT ERRORS (YES/NO)  : NO
COEFF. NORMALIZED (YES/NO)   : YES
CONSTANT GM [M^3/S^2]        :  0.39860050000000E+15
CONSTANT A [M]               :  0.63781370000000E+07
CONSTANT FLAT [-]            :  0.29825722356300E+03
CONSTANT OMEGA [RAD/S]       :  0.72921150000000E-04
NUMBER OF DATA SETS          : 12
DATA FORMAT (N,M,C,S)        : (2(I3,X),E15.9,X,E15.9)
END OF HEADER
DATA SET 01:   5151 COEFFICIENTS FOR 2002-05-01 00:00:00 OF TYPE glo
   0   0 -.135435996E-09 0.000000000E+00
   1   0 -.696238601E-10 0.000000000E+00
...
100  99 -.828253859E-14 -.175293932E-13
100 100 0.126298458E-13 0.554480726E-14
DATA SET 02:   5151 COEFFICIENTS FOR 2002-05-01 00:00:00 OF TYPE atm
   0   0 0.401898514E-10 0.000000000E+00
   1   0 0.225522283E-09 0.000000000E+00
...
100  99 0.722601553E-15 0.393424767E-16
100 100 0.179852658E-14 -.165148489E-14
DATA SET 03:   5151 COEFFICIENTS FOR 2002-05-01 00:00:00 OF TYPE ocn
   0   0 0.207567297E-11 0.000000000E+00
   1   0 -.209127879E-09 0.000000000E+00
...
100  99 0.510387838E-14 0.729377169E-14
100 100 0.155247629E-14 0.949324291E-14
DATA SET 04:   5151 COEFFICIENTS FOR 2002-05-01 06:00:00 OF TYPE glo
   0   0 -.960557189E-10 0.000000000E+00
   1   0 -.210970460E-10 0.000000000E+00
...
100  99 -.425918879E-14 -.166074453E-13
100 100 0.545089132E-14 -.561110987E-14
DATA SET 05:   5151 COEFFICIENTS FOR 2002-05-01 06:00:00 OF TYPE atm
   0   0 0.803510591E-10 0.000000000E+00
   1   0 0.258349385E-09 0.000000000E+00
...
100  99 -.176526235E-14 0.662645347E-15
100 100 0.524793984E-14 -.199281818E-16
DATA SET 06:   5151 COEFFICIENTS FOR 2002-05-01 06:00:00 OF TYPE ocn
   0   0 0.233590924E-11 0.000000000E+00
   1   0 -.191746994E-09 0.000000000E+00
...
100  99 0.465385317E-14 0.840468478E-14
100 100 0.218720802E-14 -.147296184E-14
DATA SET 07:   5151 COEFFICIENTS FOR 2002-05-01 12:00:00 OF TYPE glo
```

```
    0    0 -.130867539E-09 0.000000000E+00
    1    0 -.622117836E-11 0.000000000E+00
...
100   99 -.980827450E-14 -.264733486E-13
100  100 0.172324071E-13 0.133860780E-13
DATA SET 08:    5151 COEFFICIENTS FOR 2002-05-01 12:00:00 OF TYPE atm
    0    0 0.855524540E-10 0.000000000E+00
    1    0 0.290702845E-09 0.000000000E+00
...
100   99 0.406549558E-14 0.128476038E-14
100  100 0.643893462E-15 0.811294313E-14
DATA SET 09:    5151 COEFFICIENTS FOR 2002-05-01 12:00:00 OF TYPE ocn
    0    0 0.427502478E-11 0.000000000E+00
    1    0 -.204739061E-09 0.000000000E+00
...
100   99 0.487412982E-14 0.562979458E-14
100  100 0.801392000E-14 0.728205814E-14
DATA SET 10:    5151 COEFFICIENTS FOR 2002-05-01 18:00:00 OF TYPE glo
    0    0 -.129505962E-09 0.000000000E+00
    1    0 -.599107951E-11 0.000000000E+00
...
100   99 -.128849962E-14 -.120559974E-13
100  100 0.407529528E-15 0.970380292E-14
DATA SET 11:    5151 COEFFICIENTS FOR 2002-05-01 18:00:00 OF TYPE atm
    0    0 0.959166080E-10 0.000000000E+00
    1    0 0.279274424E-09 0.000000000E+00
...
100   99 -.178242566E-14 0.329597760E-14
100  100 0.161335787E-14 0.604664766E-14
DATA SET 12:    5151 COEFFICIENTS FOR 2002-05-01 18:00:00 OF TYPE ocn
    0    0 0.752176099E-11 0.000000000E+00
    1    0 -.195272771E-09 0.000000000E+00
...
100   99 0.673919890E-14 0.106280308E-13
100  100 -.122003463E-14 0.409984557E-14
```

5.2 Format of the Ocean Model Output (OCN1B)

The OCN1B products will be available in the GRACE ISDC on a daily basis using the level-1 filename convention (Case *et al*., 2002) "OCN1B_YYYY-MM-DD_S_RL.EXT.gz" where "YYYY-MM-DD" is the corresponding date, the GRACE satellite identifier "S" is fixed to X (meaning product can not be referred to GRACE-A or GRACE-B), RL is an increasing release number and EXT is fixed to asc (ASCII data). For data transfer simplification the products are gnu-zipped (suffix "gz").

Each file consists of a header with a dedicated number of lines (NUMBER OF HEADER RECORDS) and ends with a constant header line (END OF HEADER). The first part of the header is based on the level-1 instrument product header convention (Case *et al*., 2002) and gives more general information on the product (header lines PRODUCER AGENCY to INPUT FILE NAME). These lines are accomplished by a certain number of header lines which are derived from the original ocean model output header like

OCEAN MODEL NAME	:	The name of the ocean model
FORCING	:	Data set used for the forcing model
WIND STRESS	:	The name of the wind stress model
UNITS	:	Unit of barotropic sea level
LATITUDE SOUTH [DEG]	:	Southern latitude border of ocean model
LATITUDE NORTH [DEG]	:	Southern latitude border of ocean model
LATITUDE GRID SPACING [DEG]	:	Latitude grid spacing
LONGITUDE WEST [DEG]	:	Western longitude border of ocean model
LONGITUDE EAST [DEG]	:	Eastern longitude border of ocean model
LONGITUDE GRID SPACING [DEG]	:	Longitude grid spacing
NUMBER OF DATA SETS	:	Number of data fields per product (24 means hourly fields)

The following is an example for the header of the OCN1B_2001-10-31_X_00.asc product:

```
PRODUCER AGENCY              : GFZ
PRODUCER INSTITUTION         : GFZ
FILE TYPE ipOCN1BF           : 998
FILE FORMAT 0=BINARY 1=ASCII : 0
NUMBER OF HEADER RECORDS     : 31
SOFTWARE VERSION             : V1.1c
SOFTWARE LINK TIME           : Not Applicable
REFERENCE DOCUMENTATION      : TBD
SATELLITE NAME               : GRACE X
SENSOR NAME                  : Not Applicable
TIME EPOCH (GPS TIME)        : 2000-01-01 12:00:00
TIME FIRST OBS(SEC PAST EPOCH):  57826748.816000 (2001-10-31 18:59: 8.81)
TIME LAST OBS(SEC PAST EPOCH) :  57909548.816000 (2001-11-01 17:59: 8.81)
NUMBER OF DATA RECORDS       :   967680
PRODUCT CREATE START TIME(UTC): 2002-04-28 00:13:09.000
PRODUCT CREATE END TIME(UTC) : 2002-04-28 00:13:09.000
FILESIZE (BYTES)             :   3872384
FILENAME                     : OCN1B_2001-10-31_X_00.DAT
PROCESS LEVEL (1A OR 1B)     : 1B
INPUT FILE NAME              : pressol.20011101
OCEAN MODEL NAME             : BTPPHA
FORCING                      : ECMWF_0.5_DEGREE
WIND STRESS                  : LKB
UNITS                        : CM
LATITUDE SOUTH [DEG]         :  -75.375
LATITUDE NORTH [DEG]         :   65.250
LATITUDE GRID SPACING [DEG]  :    1.125
LONGITUDE WEST [DEG]         :    0.000
LONGITUDE EAST [DEG]         :  358.875
LONGITUDE GRID SPACING [DEG] :    1.125
NUMBER OF DATA SETS          :   24
END OF HEADER
```

This header is followed by the binary original output of the barotropic ocean model. To read this binary data the routine given in the appendix A can be used.

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7 Acronyms

AOD1B	Atmosphere and Ocean De-aliasing level-1B product
ECMWF	European Center for Medium Weather Forecast
DWD	Deutscher Wetterdienst
GFZ	GeoForschungsZentrum Potsdam
GRACE	Gravity Recover And Climate Experiment
ISDC	Integrated System and Data Center
NCEP	National Center for Environmental Predictions
OCN1B	Ocean level-1B product

8   Appendix

Appendix A (Software to read binary OCN1B products)

To read the binary OCN1B products a FORTRAN routine will be provided on the GRACE ISDC web page.